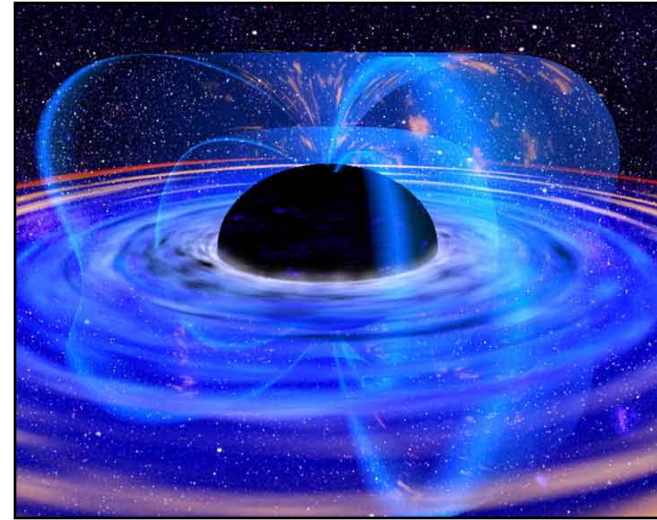# *Forming Mandrels for X-Ray Mirror Substrates*

Peter N. Blake[a], Timo Saha[a], Will Zhang[a], Stephen O'Dell[b], Thomas Kester[b], William Jones[b]

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Abstract

- **Precision forming mandrels are one element in X-ray mirror development at NASA.**

- **Current mandrel fabrication process is capable of meeting the allocated precision requirements for a 5 arcsec telescope.**

- **A manufacturing plan is outlined for a large IXO-scale program**
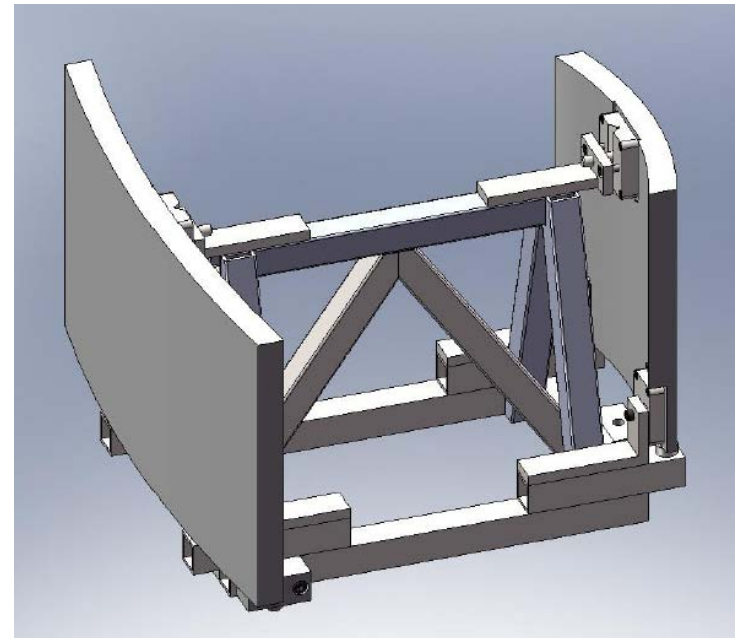
Pathfinder mandrels

The in-house pathfinder mandrels are used to produce mirror substrates utilized by all the other technology development tasks in IXO
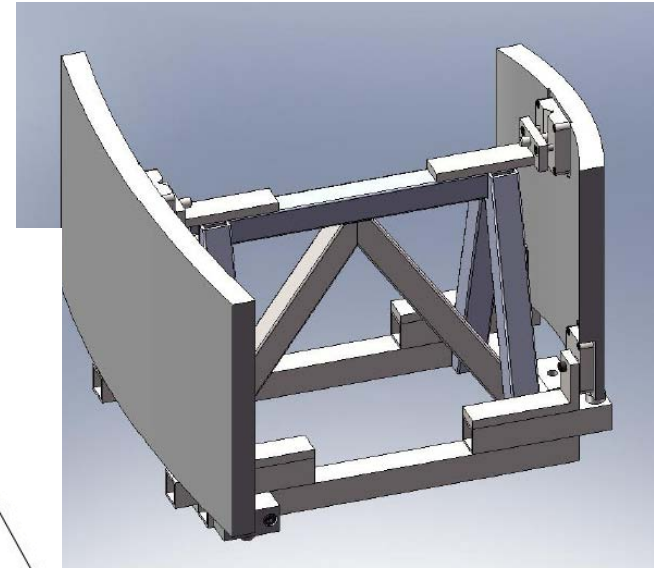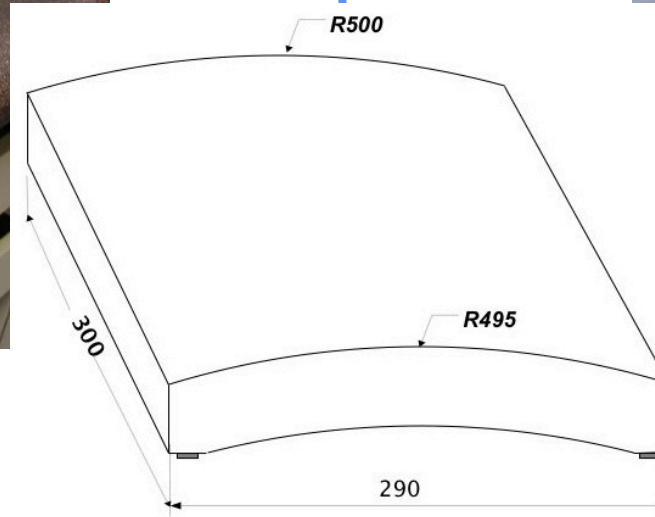
The glass slumping process:
A flat sheet of glass, 0.4mm thick, is placed atop a precision figured forming mandrel.

As the temperature ramps up to near the glass sheet's transition temperature, the glass sheet sags under its own weight to conform to the mandrel, replicating its figure.
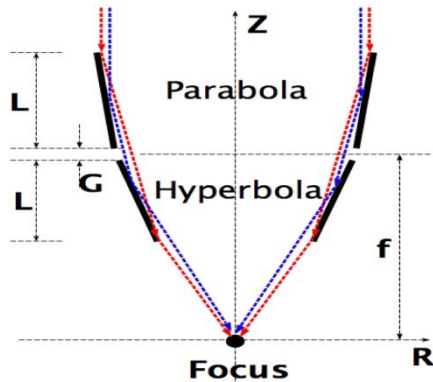
Mandrel Shape & Size

R500

R495

300

290

…from the IXO design:

	Primary		Secondary	
	Minimum	**Maximum**	**Minimum**	**Maximum**
Radius (mm)	375	1605	373	1593
Cone Angle (Degree)	0.27	1.14	0.80	3.43
Sag (micron)	0.27	1.24	0.30	1.27

IXO Mandrel Accuracy

HPD:
the half-power diameter of the focused light, derived from the optical model of a Wolter I telescope.

From this primary requirement, figure specifications for the mandrel surface are derived.

Current draft allocation

| Mandrel Surface Parameter		Error Allocation		Cumulative HPD @1.0 KeV (arcsec)
		unit	value	
Radius	Average Radius	μm	5.00	0.02
	Radius variation	μm rms	0.17	0.03
Cone Angle	Average Cone Angle	arcsec	0.40	0.18
	Cone Angle Variation	arcsec rms	0.11	0.48
Axial Sag	Average Sag	μm	0.075	0.66
	Sag variation	μm	0.050	0.69
Axial Figure	Low frequency figure (20mm-200mm)	Nm rms	23.0	1.49
	Mid-frequency figure (2mm-20mm)	Nm rms	2.0	1.53

Pathfinder Mandrels

These mandrels produce all of the mirror substrates used in subsequent development activities

- Three sets of 2: primary & secondary

- Diameters: 485 mm, 489mm, and 494mm

- 300mm length

- 35mm wall thickness

- Fused silica

- "Equal Curvature" figure (similar to Wolter type I)

- Forming surface: best 60° of exterior surface

Mandrel Polishing Machine: MPM-500
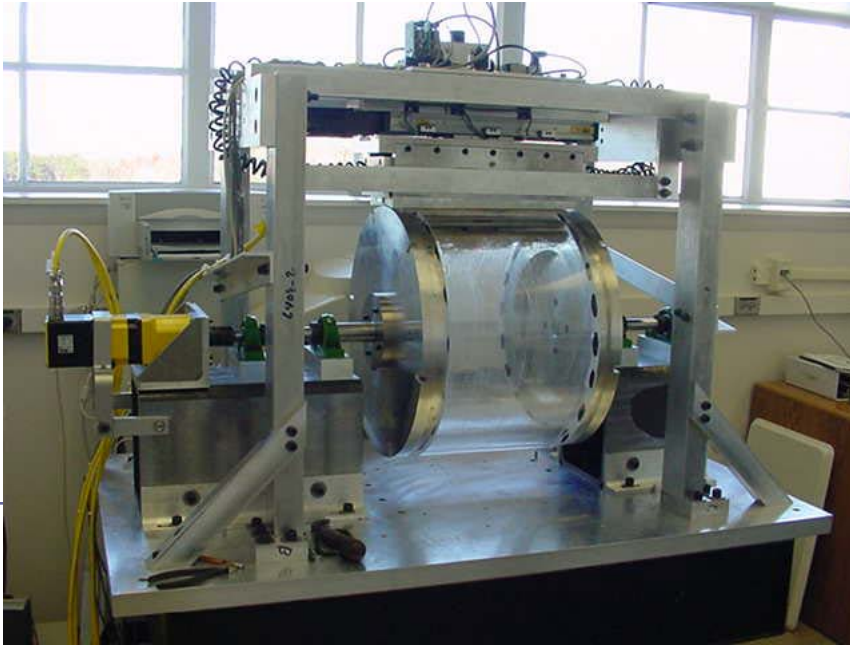
Custom machine (MPM-500) rotates mandrel about axis of symmetry and drives tool axially along mandrel. Computer control on both axes allows variable speed of mandrel and tool which can be varied during a run if required.

Current process uses a pitch lap which is shaved to remove less material at axial positions which are low. Mandrel rotated at constant slow speed, and tool driven back and forth in oscillatory motion at rapid rate to figure out axial errors.

Metrology at MSFC:
Vertical Long Trace Profilometer: VLTP
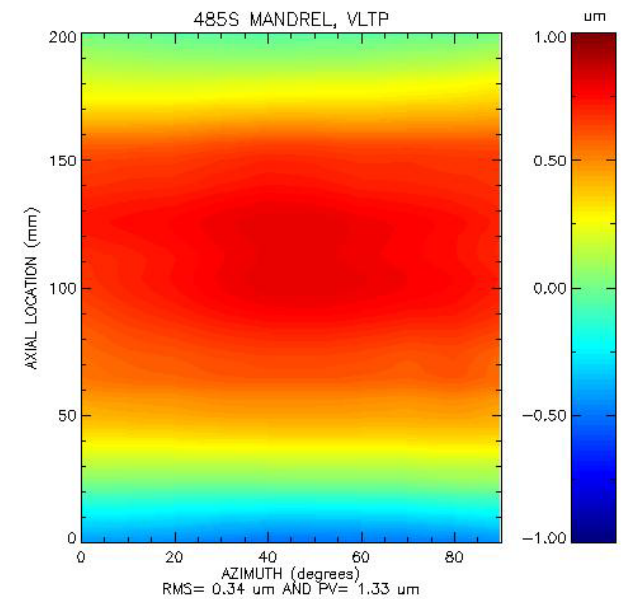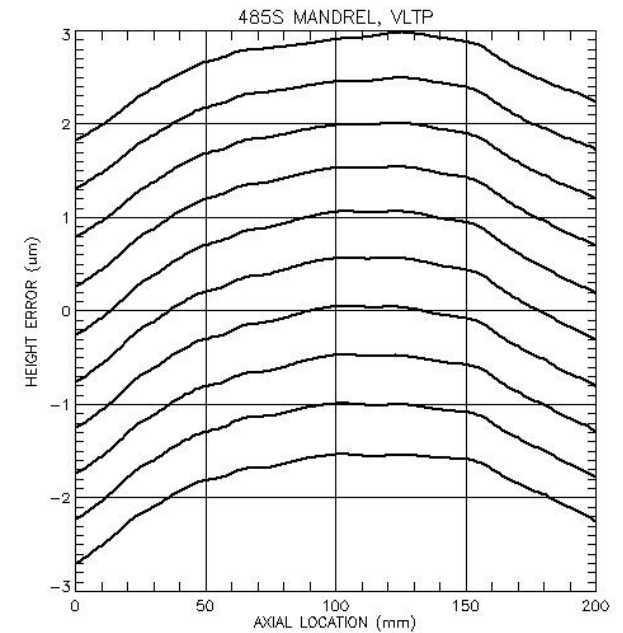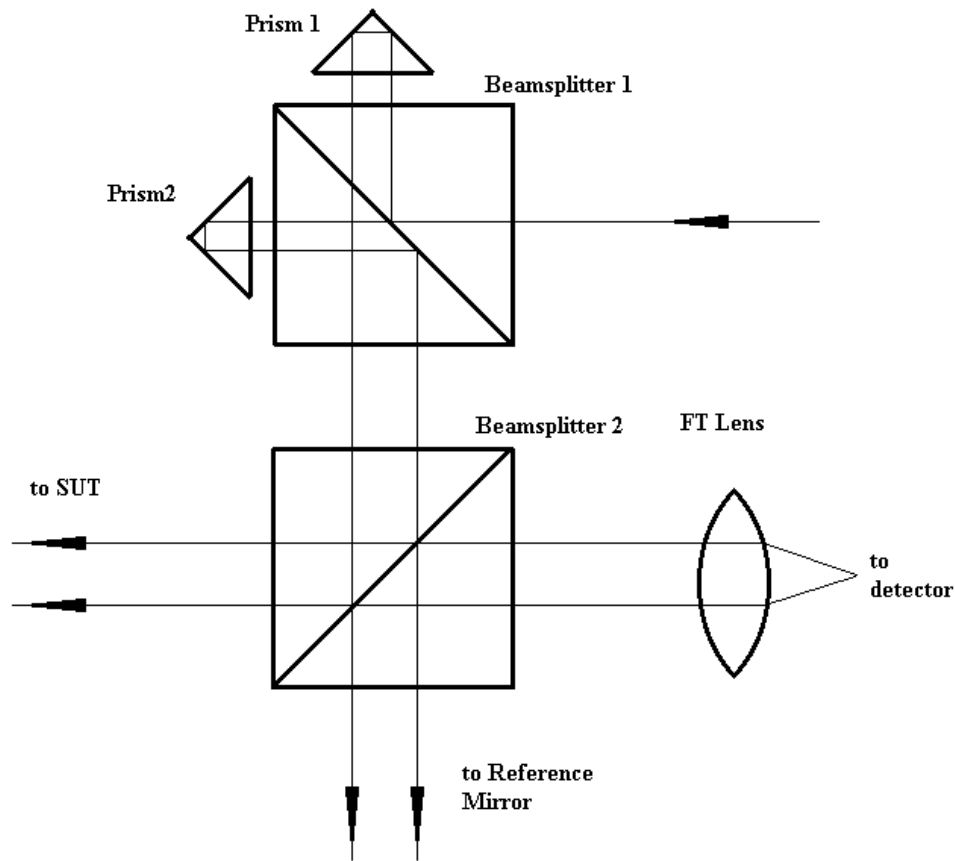
Metrology at GSFC

An interferometric measurement in collimated space is made of the axial figure: a defocused line -- every 10°.

489S-090423, FIGURE ERROR

RMS=0.31 um AND PV=2.63 um
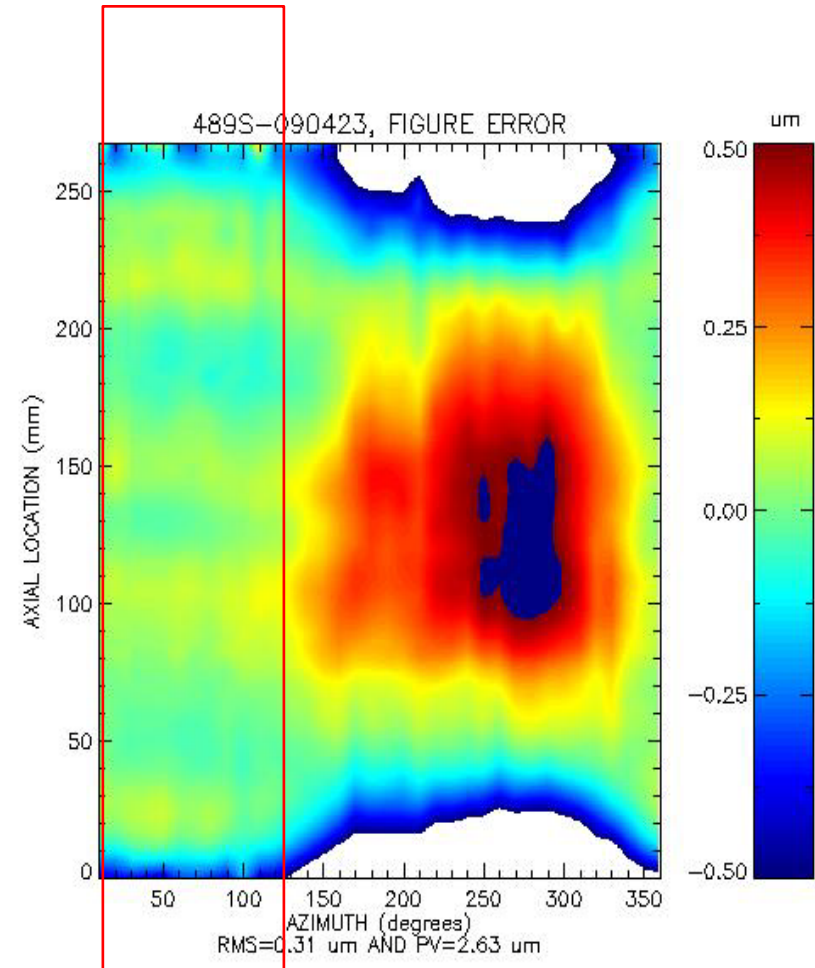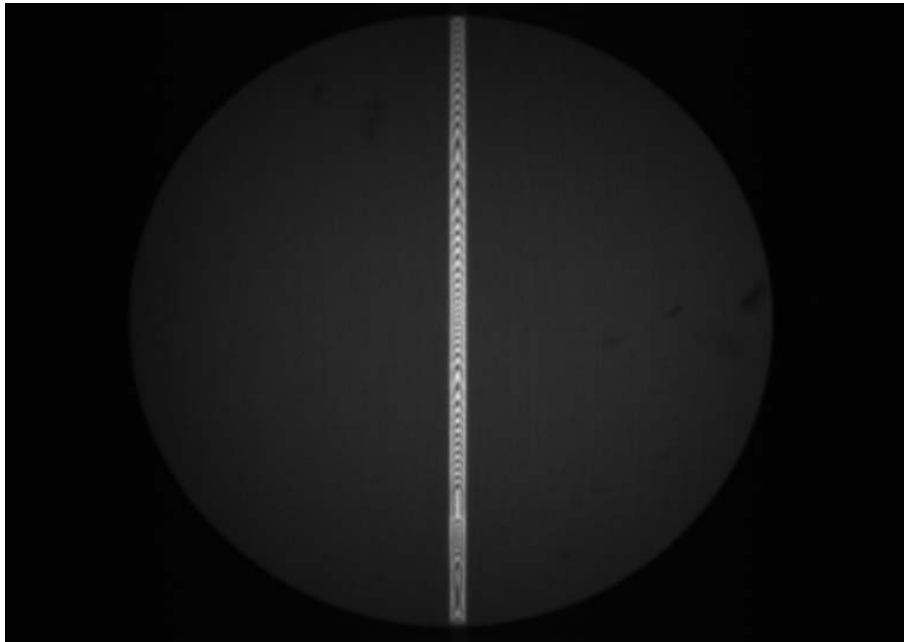
We use the best 90-degree segment: peaks are only about 0.1 µm high

Four instruments

- PSDs of the data agree reasonably well at low spatial frequencies up to 0.04 mm^{-1} (spatial period = 25 mm)

- Without a null lens (collimated space), interferometer data is not reliable below ~25 mm

- Our current process does not create errors between 2 and 25 mm, and the replication process does not replicate errors below 2 mm, so we are confident in the filtered interferometer data

24"ZYGO
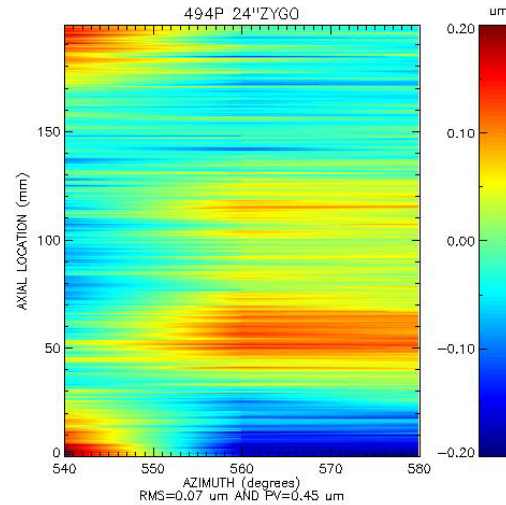
ZYGO/Verifire
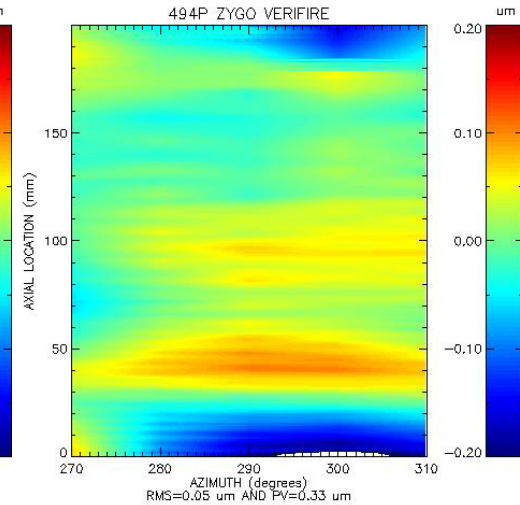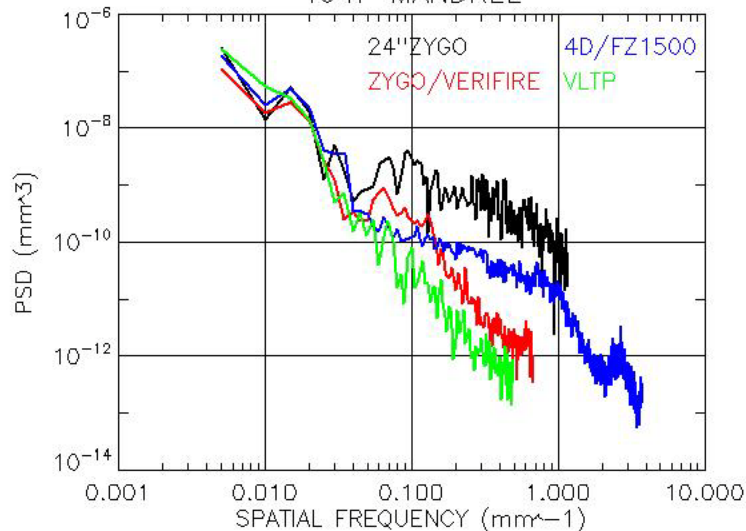
4D/FZ1500
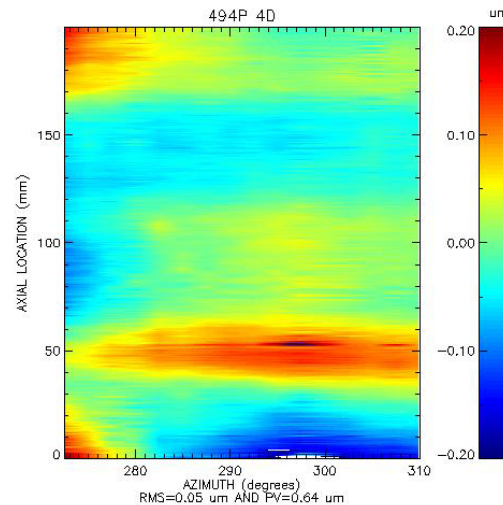
VLTP
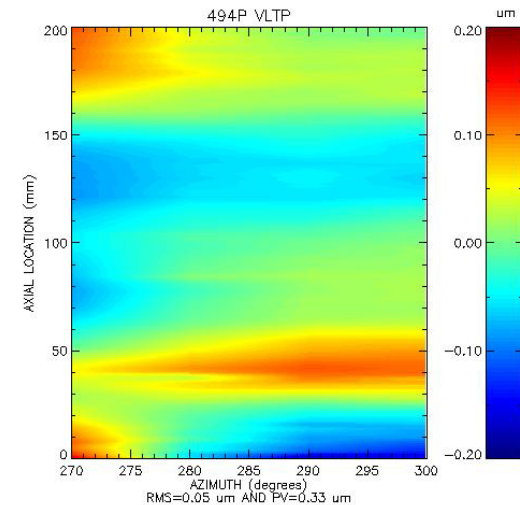
Optical performance

- **Half-power diameter**
  - **Calculated from diffraction integral at 1.0 KeV**
- **Calculated in 270 to 310 degree area of the mandrel**
- **Radius and cone angle variations are not included**
- **High frequency errors increase the HPDs of interferometrically measured data, but when filtered, the results are consistent across the instruments**

Measurement Instr.	HPD (arcsec)
24"ZYGO (filtered d =30mm)	1.7
ZYGO/Verifire	2.0
4D/FZ1500	2.5
VLTP	1.8

Filtered (d=30mm)	HPD (arcsec)
24"ZYGO	1.7
ZYGO/Verifire	1.3
4D/FZ1500	1.7
VLTP	1.6

Design of a Flight Program Process Sequence

Our Current process sequence:

– **Generate Cone of correct radii and cone angle**

– **Lap and polish out the sub-surface damage**

- **Removing the many fine lines, ridges & mid-spatials**

- **Keep figure within 1 micron**

– **Polish with MPM-500 to final figure**

- **Current achievement: 0.2 µm P-V figure error & 1.5 arcsec HPD**

▪ **Note:**
over the central active area, the departure from a pure cone is one micron.

Mid-spatial Frequency Remediation (1):

The most difficult of the specifications is the mid-spatial frequency error:
2 nm rms

1. Amplitude reduction:

  – High points are measured, registered and chased down:

Problem:
You haven't reduced the slope

tool direction

Starting Surface Form

Surface Form after small tool Correction -1

Surface Form after small tool Correction -2

Amplitude

Spatial Scale Length
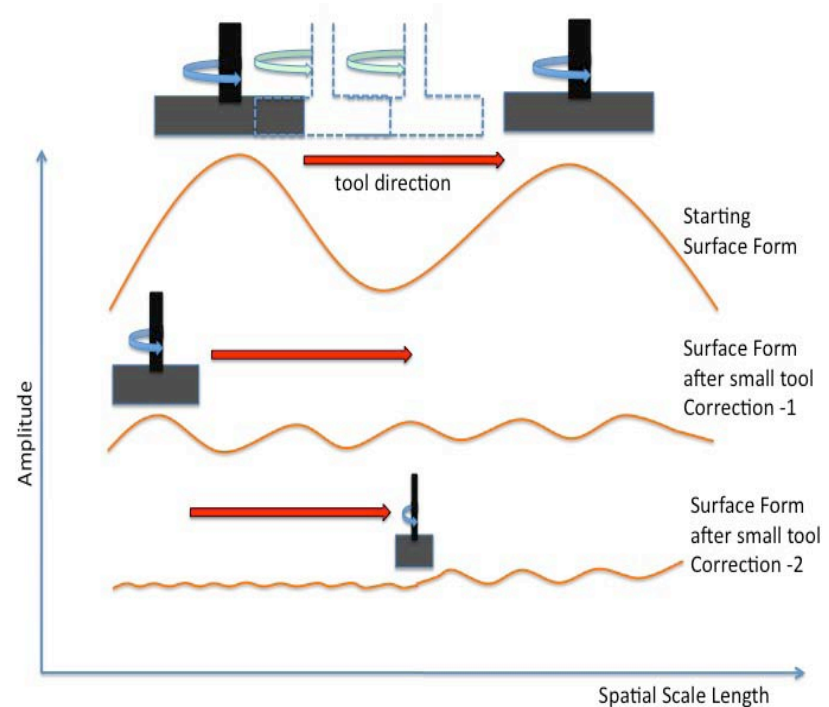
Mid-spatial Frequency Remediation (continued):

2. **Smoothing:**

    – **Large aperture tooling**

    – **The stiffness of the polishing tool bridges the peaks, creating higher pressure on the high points**

    > **…ceases to work when the slope of the error is too small (~one wave/mm)**

3. **Prevention:**

    Some of the sources of MSF error are:

    - **Overlap in rastered sub-aperture tool paths**

    - **Machine tool motion control overshoot**

    - **Machine vibration/tool resonance**

    - **Cyclical tool wear**

    - **Tool deformation**

    - **Cyclical instability in any of the above effects**

…this strategy places high requirements on stiffness of the machine, accuracy of the slides, and control & measurement of tool wear: making the machines very expensive

Baseline Process and tools

Our current baseline uses option 2 – large aperture smoothing – for MSF remediation

The current baseline sequence is:

1. Generate cone (fixed abrasive grinding) to within 10 microns of cone

2. Lap with fixed abrasive and large tool to conical figure within 3 µm

3. Large-pad polish, maintaining conical figure at 3 µm

    -- at this point, all of the MSF ripple has been taken out, the subsurface damage reduced to one micron, and the surface is very close to a pure cone

    -- the material remaining to be removed is on the order of 1 cc

4. Final figure correction using ion-beam figuring (IBF), magneto-rheological finishing (MRF), or sub-aperture polishers

The Cell

**Note: only the final machine cost $1m…
        and it is used only a few hours on each mandrel.**

- **The first machine costs about $50K**

- **The intermediate full-aperture machines cost perhaps $120K, with programmed dwell-paths to keep the generated figure within 3 microns**

An orchestra of machines, collected into a cell:

- **each dedicated to a single component correction**

- **each occupying a distinct place in the sequence**

- **Each having an instruction set for the machine operator specifying settings and times as functions of the measured surface error components**

Metrology

- **A metrology station has been design by Praecis and Zeeko:**

  - **Using an error budget to set individual subsystem error limits, while making trade-offs that balance the level of difficulty among the subsystems**

  - **A profilometer with probe system positioning accuracy in the radial direction, during a single axial scan: 1 nm rms**

Large-Pad conical polisher

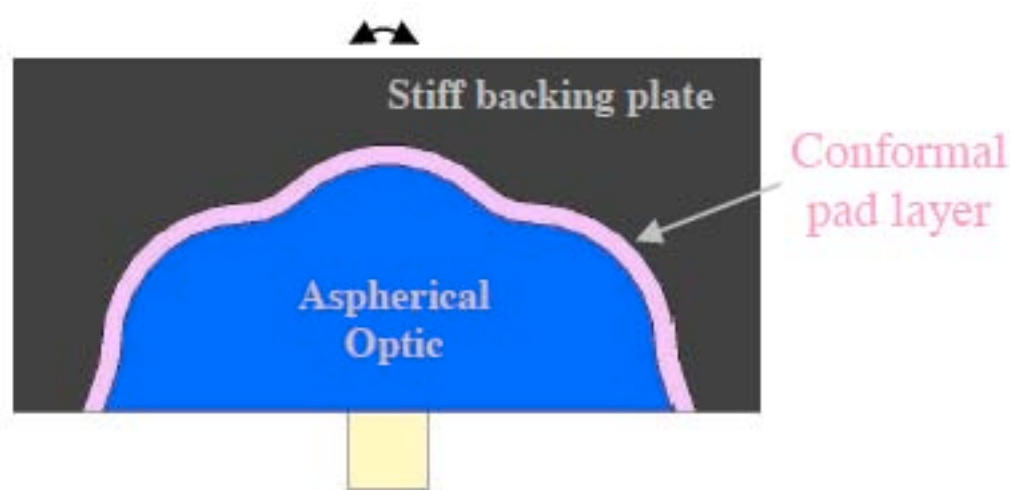- **A large-pad machine for lapping and polishing cones, removing all mid-spatial frequency error, while improving form error from 10 μm to 3 μm, is being designed by Aperture Optical Systems:**
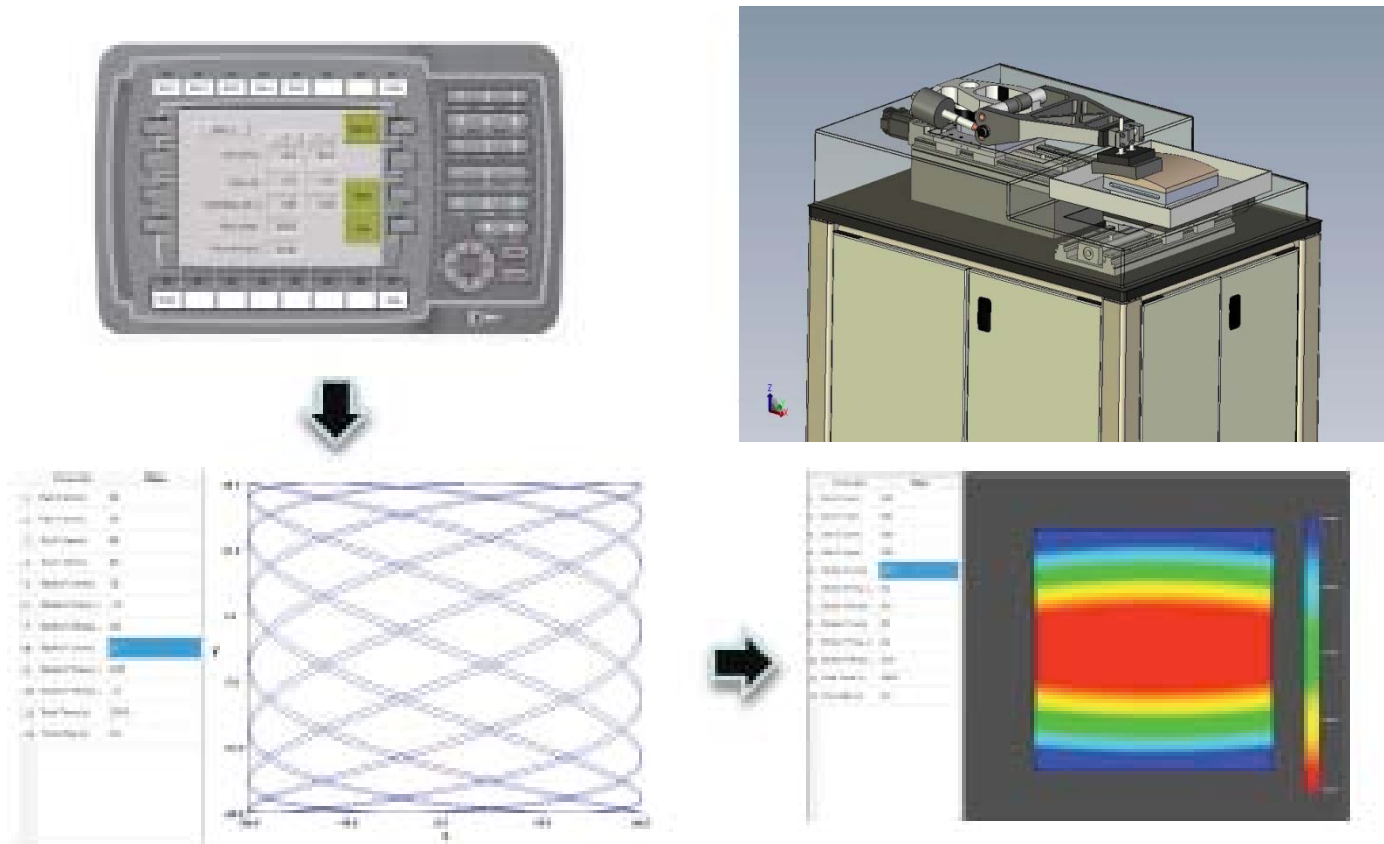
Smoothing by Ultrasonic Vibration

- **A very different large pad polishing process, using tiny ultrasonic strokes, called "VIBE" is being developed by Optimax Systems:**

Conclusion

- A baseline plan for fabrication of many hundreds of x-ray mandrels has been developed. An operational specification of 1.5 arcsec HPD is translated into fabrication shop surface specifications.

- These can be economically met with a designed production sequence based on producing conical surfaces meeting the mid-spatial frequency error specification through large-pad polishing, and completing the figuring with one of the modern precision sub-aperture machines.

5 mm form accuracy

Stage 1

Abrasive Grinding: generate cone …to10 microns

10 µm form accuracy

Stages 2-3

Computer-controlled large pad lapping & polishing

3 µm form accuracy

Stage 4

Computer-controlled sub-aperture correction

5 nm form accuracy